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# An integrated framework for damage diagnosis and prognosis in long-term structural health monitoring

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## ABSTRACT

This work presents an integrated framework for longer-term structural health monitoring (SHM) based on hysteresis loop analysis (HLA). Hysteresis loops has proven an effective indication of damage assessment in civil engineering structural health monitoring (SHM). It provides rapid, near real-time report on damage states for immediate post-event diagnosis using a trained deep learning network (DLN) model. Stiffness evolution and its exact values are identified using the HLA method, enabling a more detailed analysis and providing foundation to create a computational model for further analysis of risk of damage and collapse. With the resulting predictive, nonlinear model, an incremental dynamic analysis (IDA) is performed to assess risk of damage or probability of collapse. This IDA enables, in turn, financial loss estimates based on known risk and accurate predictive models for optimal decision-making. Therefore, the overall integrated SHM framework is not only damage diagnosis and localization, but extends these results to create reasonable baseline dynamic models for forecasting structural performance and predicting remaining life, which in turn enable automated structural and financial risk analyses.

A case study of the proposed framework using experimental data from a 3-storey apartment structure tested at the E-Defence facility in Japan is presented. Results show predicted linear and nonlinear responses match very well with the experimental data using the foundation model created from the HLA SHM results, indicating it provides a very accurate representation of the real damage states that would occur. The combined IDA analysis enables the updating of collapse fragility curves as subsequent events occur, and provides the results to quantify seismic induced financial losses in longer-term monitoring. The overall framework takes SHM from a tool providing data into automated prediction analysis by "cloning" the structure using computational modelling, which in turn allows optimised decision making using existing risk analyses and tools.

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# 1 INTRODUCTION

Seismic damage is a major risk in seismic zones with significant follow-on social and economic impacts, and the resulting local damage may have a great impact on the overall health or state of the structure, which can increase the potential risk of building collapse and loss of lives in an aftershock or new event in the future. Rapid retrofit would be necessary to increase the safety levels of damaged structures to their adequate safety requirement, as well as their ability to stand under the potential damage. However, retrofit funding to achieve extremely high safety standards may be limited to the reality of economics and government policy, where making an optimal decision for the owners with limited experience of engineering analysis may be difficult. Therefore, there is a significant need to develop a performance-based framework with explicit, quantified properties for owners, insurers, and decision makers presiding over cities with many damaged structures.

Establishing retrofit priorities requires an estimation of the probability of current and potential future damage (Williams and Sexsmith 1995). Traditionally, story deformation and energy dissipation demand were used for damage assessment or collapse prediction (Powell and Allahabadi 1988). However, structural safety against nonlinear dynamic instability cannot be ensured by simply limiting the maximum story drift (Bernal 1992; Williamson 2003). In addition, energy dissipated in small amplitude cycles could significantly exceed the energy dissipated up to failure, which may not be reflected in some simplified seismic design methodologies for low cycle fatigue (Teran-Gilmore and Jirsa 2005). Equally, collapse capacity is highly affected by the nature of ground motions and changes of structural properties due to damage and/or structural reconfiguration (Zareian and Krawinkler 2007). Thus, post-earthquake assessment of damage and vulnerability to aftershocks based on a nonlinear dynamic analysis is considered essential to account for the evolution of material behaviours and structural properties under varying dynamic loads (Villaverde 2007).

Structural health monitoring (SHM) provides methods to detect, localise, and quantify damage after earthquakes. Although there is a wide range of SHM methods available in the literature, they have mainly focused on turning data into estimations of current structural properties, whose changes can reflect damage. However, very few SHM methods offer results immediately post-event, and many require human input, which may not be available (Moaveni et al. 2012).

More importantly, SHM does not provide a ready, quantified tool for assessing, the ongoing safety of a structure or the, likely now modified, risk of collapse. There has been a lack of framework to extend SHM from a damage-monitoring role into a more comprehensive risk assessment process for both immediate use and longer-term decision-making. Therefore, an accurate, predictive foundation computational model made from the SHM results would enable dynamic assessment and risk prediction of further damage or collapse in the subsequent shocks for optimal decision-making. In essence, the automated creation of a digital structural model or "digital clone" of the damaged post-event structure from SHM results would enable equally automated structural and financial future risk analyses and optimised decision-making (Mander et al. 2007), where digital clones are emerging as a multi-billion dollar tool in other industries (The Economist 2016).

This paper suggests an integrated framework to provide a rapid, automated and quantified damage assessment after a major event and risk analysis of damage or collapse in the future, enabling more optimal decision-making for owners and occupants. The procedure is presented using case study of a full-scale 3-story apartment building tested on the E-defence shake table in Japan (Zhou et al. 2017).

# 2 RISK ANALYSIS: A CONCEPTUAL FRAMEWORK

One possible conceptual framework for seismic risk analysis is shown in Figure 1. The overall approach is based on the hysteresis loop analysis, where hysteresis loops have proven effective in seismic performance-based analysis and designs in terms of capture nonlinear dynamics (Cifuentes and Iwan 1989; Iwan 2002; Xu et al. 2014; Zhou et al. 2015). Detailed explanation of key steps are given in the following sections.

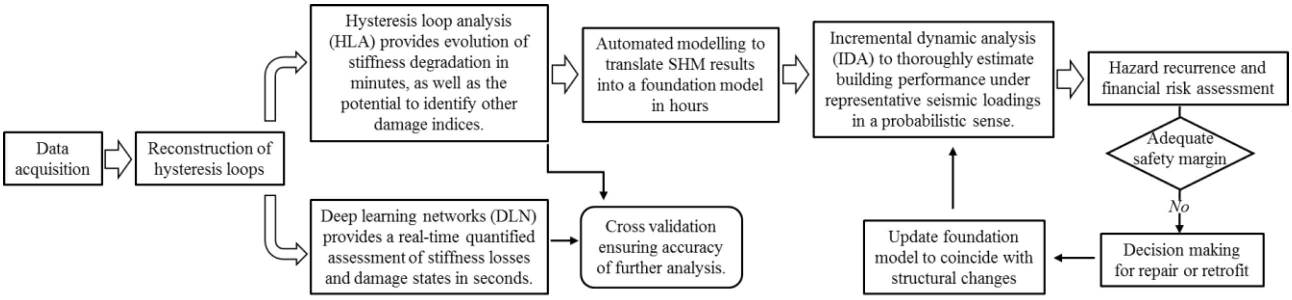


*Figure 1: A framework for seismic risk analysis based on SHM damage quantification and localisation, and the creation of predictive nonlinear models or "clones" to enable future risk assessment.*

## 2.1 Seismic data acquisition

Real-time data acquisition from an instrumented structure has become a readily possible reality with the significant development of innovative sensors (Spencer Jr et al. 2004; Hsieh et al. 2006; Baptista et al. 2012). Noisy accelerations, velocities and displacements can be corrected with advanced GPS method (Hann et al. 2009), although measuring displacement is still expensive in reality. Current research has shown the possibility of constructing hysteresis loops in a near-real time fashion (Iwan 2002; Xu et al. 2014; Zhou et al. 2015). Therefore, reconstruction of accurate hysteresis loop immediately after earthquakes is entirely feasible, where sensor technology advances will make this task increasingly accurate and lower cost.

## 2.2 Deep learning network (DLN)

Histograms of stiffness can be extracted from hysteresis loops for training a DLN model to estimate the pre-defined target values relevant to damage states. Training the DLN model is time consuming with a large number of data sets. However, the trained model can be readily used once trained, and thus can provide initial damage estimation results in seconds. Therefore, the DLN estimation is model-free and can be used a quick indicator of damage assessment and structural safety, as well as providing a baseline for further more detailed SHM analysis. These models can also be made quite general to a wide range of structures.

## 2.3 Hysteresis loop analysis (HLA)

The model-free HLA method is a mechanics-relevant SHM approach, and has shown its ability to accurately identify nonlinear changes in structural stiffness and other properties in an entirely automated fashion (Zhou et al. 2015; Zhou et al. 2017; Zhou et al. 2017a). The identified change of stiffness from HLA is available across individual stories, enabling a more detailed analysis for damage assessment and identification of other dynamic properties. It has also demonstrated the ability to track these stiffness changes across multiple nonlinear events (Zhou et al. 2017). More importantly, SHM results from HLA provides foundation damage assessment in terms of stiffness changes at the story or finer level to back calculate and identify an assumed computational foundation model for further analysis of risk of damage and collapse.

## 2.4 Automated modelling

Automated model creation or the creation of a "digital clone" (The Economist 2016) enables potentially automated dynamic analysis within minutes if necessary, providing better data to optimise decision-making and reduce uncertainty. However, the model-free HLA or DLN methods do not directly yield a model to simulate further outcomes. Therefore, automated modelling approaches using SHM results to create actionable, accurate and, critically, predictive computational models could provide potentially significant benefit. Importnatly, model-free methods avoid constraints to a single or fixed baseline model, and thus suffer less from errors due to poor model selection for SHM (Zhou et al. 2017a). Although a nonlinear model still needs to be assumed for further dynamic analysis, SHM results can provide more evidence or *a priori* knowledge for model selection.

### 2.5 Incremental dynamic analysis (IDA)

IDA is a parametric analysis method used to more thoroughly estimate building performance under seismic loading to quantify the relationship between seismic capacity and demand, potentially leading to evaluation of financial risk (Vamvatsikos and Cornell 2002). A series of nonlinear dynamic analysis are performed by subjecting the foundation model to varying ground motion records scaling the intensity in increments until global collapse is reached. The IDA has proved a valuable tool to give a clear indication of the relationship between the seismic demands on structures and their global capacity (Mander et al. 2007). However, IDA is highly dependent on the input ground motion and the accuracy of computational model, which introduces aleatory and epistemic uncertainty in quantifying collapse capacity (Zareian and Krawinkler 2007). Therefore, IDA is suggested to be performed using a range of representative ground motions and parameter dispersion is taken into account for modelling uncertainty (Kennedy and Ravindra 1984; Cornell et al. 2002).

### 2.6 Risk assessment for decision making

The results of IDA explicitly address the probability of collapse or safety margin with more intuitive estimates of losses caused by an earthquake. What is challenging is how to translate the IDA results into a retrofit decision. One possible application could transform IDA results into a financial implication of damage using expected annual loss (EAL) (Mander et al. 2007). The calculated EAL can be used to estimate the likely cost of recovering a structure or similar structure across located in the same region to the safety standard, where the owners can decide based on the EAL for the current structure or after (a modelled) retrofit which outcome offers the best financial outcome. It is thus provides a pragmatic way to allocate limited funds for repair or to determine if it is more optimal to demolish some damaged structures.

## 3 CASE STUDY

The employed structure is a full scale 3-story steel moment resisting frame (SMRF) building tested in the E-defence shake table in Japan (Zhou et al. 2017). Assessment of seismic damage is investigated over 6 input ground motions in both x and y horizontal direction, as listed in Table 1. Accelerations and displacements are measured at each floor to reconstruct 3 hysteresis loops in each (x, y) direction for each event. More details on the reconstruction of hysteresis loops for MDOF systems can be found in (Zhou et al. 2017).

*Table 1: Sequential shake table tests and PGA in each direction (x,y,z).*

| Test No | Input event | PGA *y*-direction | PGA *x*-direction | PGA *z*-direction |
|---|---|---|---|---|
| #01 | BSL2-18% | 0.11 | 0.13 | 0.01 |
| #02 | Sannomal | 0.22 | 0.16 | 0.01 |
| #03 | Uemachi | 0.30 | 0.35 | 0.01 |
| #04 | Toshin-Seibu | 0.62 | 0.63 | 0.06 |
| #05 | Sannomal | 0.21 | 0.15 | 0.01 |
| #06 | Nankai-Trough | 0.87 | 0.74 | 0.03 |

The DLN model is trained using simulated data from 20,000 virtual buildings including a wide range of dynamic behaviours and ground motions. Damage assessment using both DLN and HLA are implemented in $x$ and $y$ directions over the 6 earthquakes. The identified stiffness changes in the $y$-direction for both methods are compared in Figure 2, which shows a very good match in the trend of stiffness drops over the events. Damage assessment using the pre-trained DLN model can be done in seconds, providing rapid notice of damage defined by stiffness degradation, as listed in Table 2 (Carrillo 2015) or other methods. However, the DLN does not provide true stiffness values and cannot be used to create a nonlinear computational model.

*Table 2: Damage states of stiffness degradation.*

| DI | Damage states | Repair required |
|---|---|---|
| 0~0.10 | No damage | Immediate occupancy |
| 0.10~0.20 | Minor damage | Inspect, patch |
| 0.20~0.40 | Moderate damage | Repair components |
| 0.40~0.70 | Major damage | Rebuild components |
| >0.70 | Collapse | Rebuild structures |

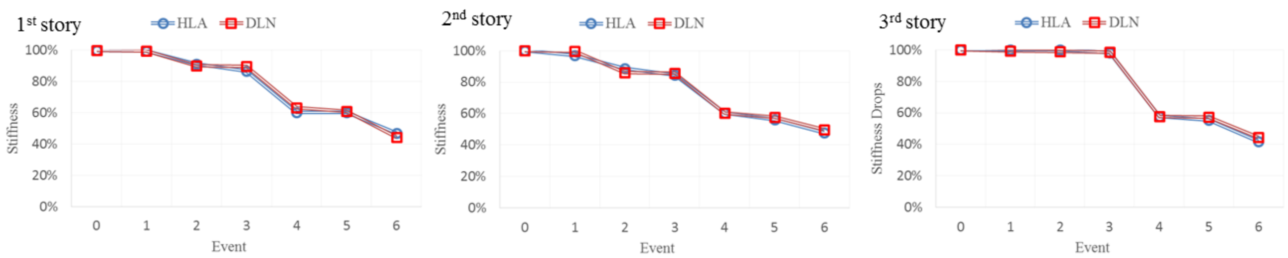


*Figure 2: Comparing predicted stiffness drops between DLN and HLA for each story over 6 earthquakes.*

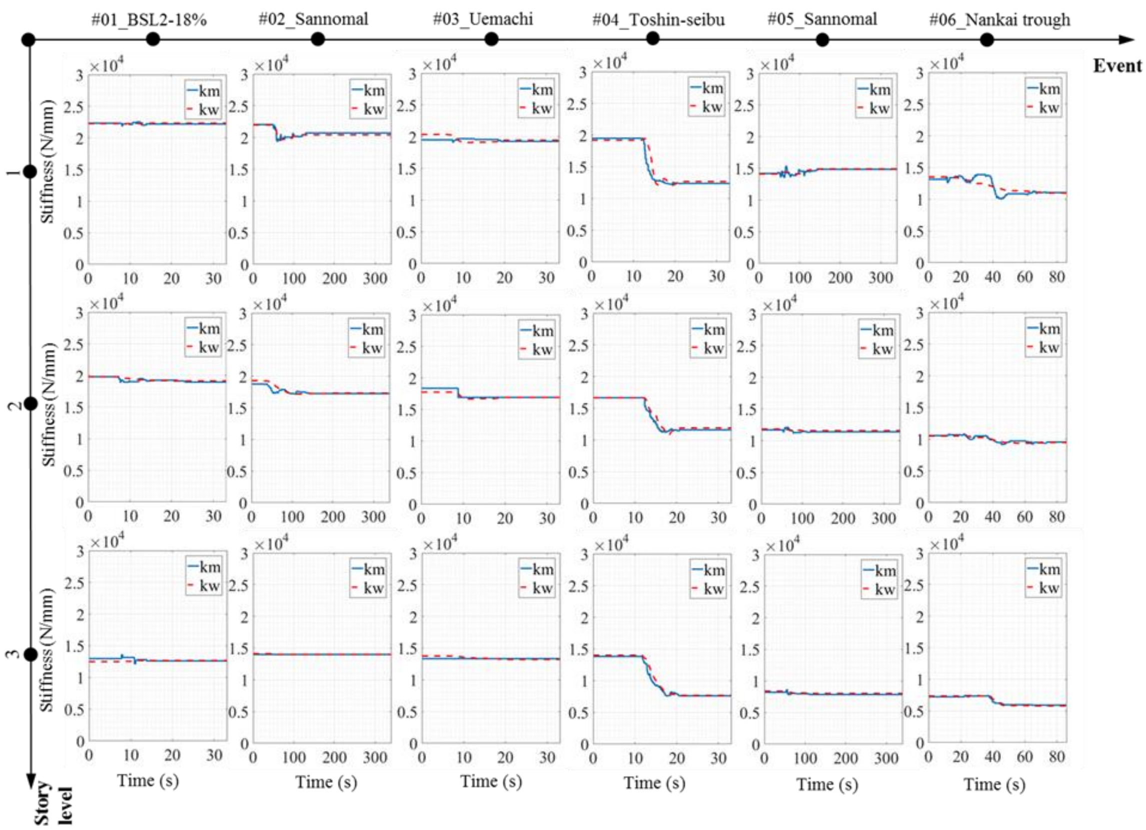


*Figure 3: Identified evolution of HLA stiffness for each story over 6 earthquakes.*

Figure 3 presents the identified evolution of the actual stiffness values of each story using HLA method. It is important to note the final stiffness values for each event are within 5% of the next event's initial identified stiffness value. This event-to-event consistency and accuracy is evident for each storey and event in both directions. Therefore, HLA results can be used to back calculate and identify system parameters for an assumed hysteretic foundation model (Wen 1976) in an automated fashion.

The automated foundation model yields a good match between the modelled and measured response with correlation coefficients $R_{corrcoef}$ =0.94, 0.92, 0.89 for the first, second and third story, respectively, as shown in Figure 4. More importantly, the predicted response for the following stronger event EQ6 using the foundation model also match well with the measured response with $R_{corrcoef}$=0.93, 0.95, 0.91, as shown in Figure 5. Therefore, the overall results indicate the possibility of creating a model using HLA results for response and damage prediction to future events, and thus provide a more accurate computational model for incremental dynamic analysis.

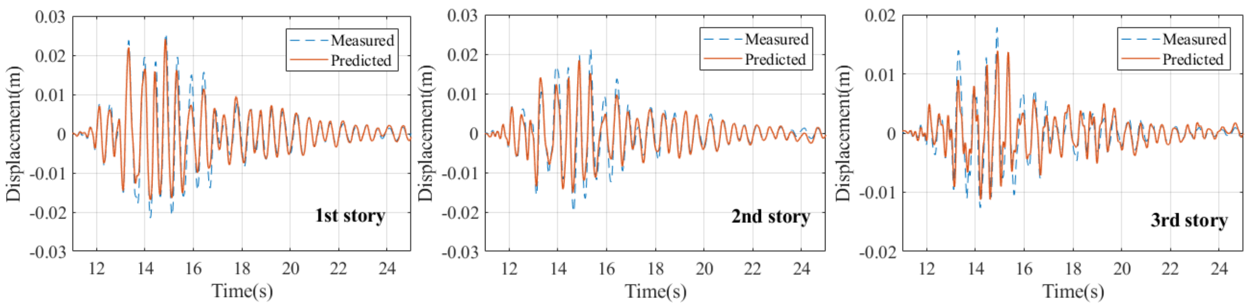


*Figure 4: Comparing modelled and true displacement response of EQ4 for the experimental building.*

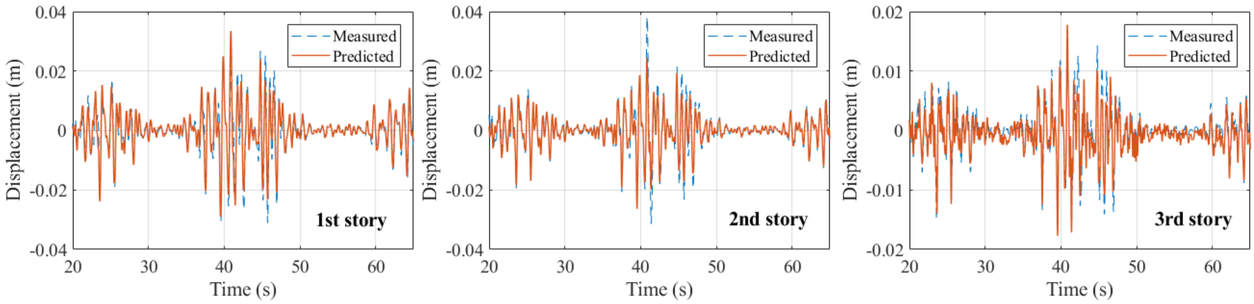


*Figure 5: Comparing predicted and true displacement response of EQ6 for the experimental building.*

There is no unique definition to characterize the intensity of an earthquake record in IDA. In this case study, spectral acceleration at the structures first mode period has been used as the intensity measure (Adam and Jäger 2012). In addition, the analysis is performed for a range of 60 ground motions (Somerville 1997), providing a range of ground motion spectra and thus adding robustness to the results. Collapse capacity in all cases was identified through scaled magnitude of the ground motion until collapse. The IDA curves generated for incremented magnitude for each earthquake until collapse are shown in Figure 6. It shows the effects of different earthquake ground motions on the specified proof of concept structure.

Probability of collapse based on log normal distribution can then be calculated by counting the collapse capacity values of all ground motions, which could then be used to determine damage loss in a financial sense expressed by the expected annual loss (Mander et al. 2007). It is important to note assessing probability of collapse using IDA is complicated and significantly affected by structural and earthquake uncertainties (Villaverde 2007). Hence, it is still challenging to develop an efficient method considering all types of uncertainty in the assessment of collapse.

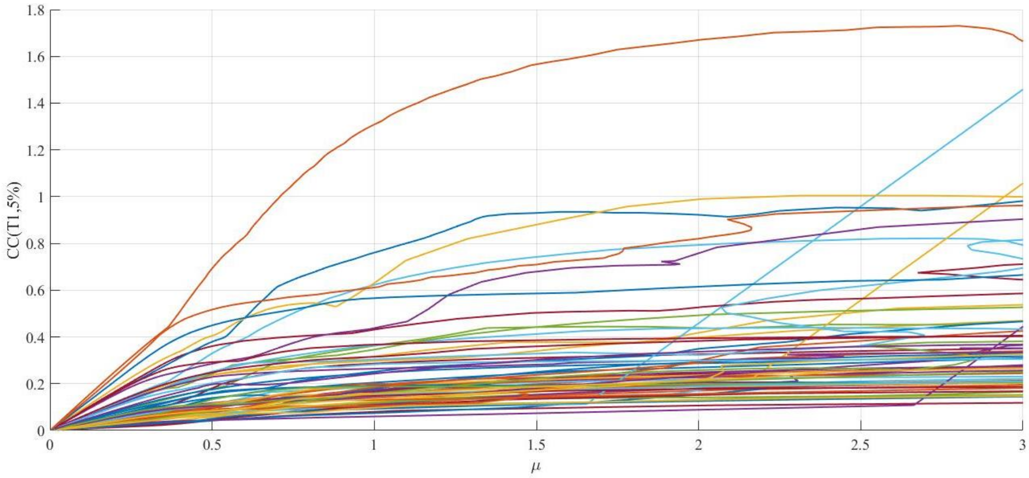


*Figure 6: IDA curves for a standardised set of 60 earthquake records.*

Limited information is known for the collapse mechanism of real structures in code provisions, while “digital clones” feed virtual models with real world data to significantly improve the confidence of testing structures against damage/collapse before aftershocks and new events, which would thus improve efficacy of decision making and reduce the cost and time on maintenance. As similar or even same buildings regardless of construction variability could be built in the same region, the virtual part of the assessment framework can be readily extended without additional cost from vertical to horizontal for the same types of buildings, where similar platform over a range of industries have shown billions of dollars in saving over the lifetime of product (The Economist 2016).

## 4 CONCLUSION

This paper proposes an overall concept to extend SHM from damage assessment tool towards a potentially far more valuable predictive future risk analysis tool to optimise decision-making. Given proven SHM methods, such as the HLA method used in this case study, what is required the damage and localisation data exists to create accurate, predictive nonlinear models to predict future responses of the now-damaged structure. The case study demonstrates the potential for this model creation to be automated, which along with automated SHM using the HLA method, provides the capability to go from identified damage to nonlinear automated modelling to automated analysis of these models with results including future structural and financial risks and costs, which can be used to optimise decision-making.

Overall, this concept employs SHM damage data to create “digital clones” of damaged structures for analysis to guide decision-making, which is a major extension of the role of SHM from monitoring tool to automated decision-making system. More specifically, “digital clones” are emerging in a range of industries, and this concept brings them to structural and earthquake engineering, where their potential could be significant, both socially and economically.

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